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Initial Results from the Lunar Reconnaissance Orbiter Laser Ranging Investigation

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Abstract

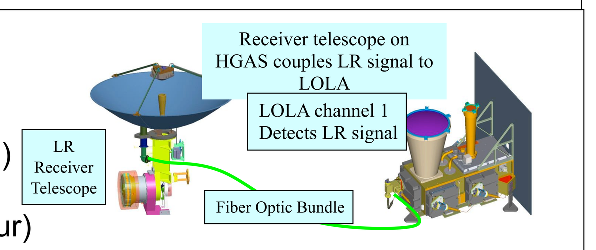
The Lunar Reconnaissance Orbiter (LRO) Laser Ranging (LR) system will enabling the spacecraft to achieve its precision orbit determination requirement. The LR is routinely making one-way range measurements via laser pulse time-of-flight from the Earth to LRO. The LR consists of a receiver telescope mounted on LRO's high-gain antenna that captures the uplinked laser signal, and a fiber optic cable that routes the signal to the Lunar Orbiter Laser Altimeter (LOLA) on LRO. The LOLA receiver electronics record the time of the laser signal and provide it to LRO's data system. The LR ground system consists of laser ranging stations that times and transmits the laser pulse, a data facility, and the LOLA Science Operations Center. The primary ground station is NASA's Next Generation Satellite Laser Ranging System (NGSLR) in Greenbelt, MD, and successful ranging has also been accomplished by MOBLAS-7 at Greenbelt, MLRS at Fort Davis, Texas, Herstmonceux in England, and Zimmerwald in Switzerland. Other approved stations in the International Laser Ranging Service (ILRS) will participate in the future. LR measurements permit improvement in the geodetic positioning of LRO to the sub-meter level with respect to the Moon's center of mass. Positioning by the LR will enable the determination of a three-dimensional geodetic grid for the Moon based on the precise seleno-location of ground spots from LOLA. Current performance indicates 48-cm single-shot range error, or 24 cm with refined calibration. Up to an order of magnitude improvement can be expected from shot averaging.

Laser Ranging (LR) Objectives

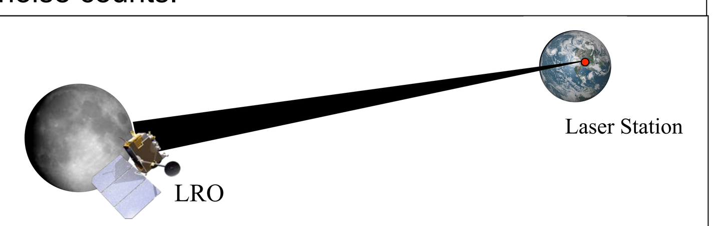
- The objective of LR is to contribute to the accurate calculation of LRO orbits. Precise orbit determination (OD) allows generation of accurate topography from LOLA's measurements.
- Designed to measure centimeter-level orbit perturbations over a few seconds and meter-level perturbations over the entire LRO.

Lunar Reconnaissance Orbiter (LRO) – Laser Ranging (LR) Overview

- Flight Segment:
  - 3.81 cm diameter aperture mounted on High Gain Antenna
  - Fiber optic bundle carries the light to the LOLA detector #1
  - LR FOV is ~ 1.7 deg (earth diameter is ~2 deg as viewed from moon)
  - 532 nm bandpass filter with 0.3 nm FWHM
  - Ultrastable OCXO oscillator: Symmetricom 9500 (2x10-12 over 1 hour)
  - Onboard software controls threshold setting using detector noise counts.

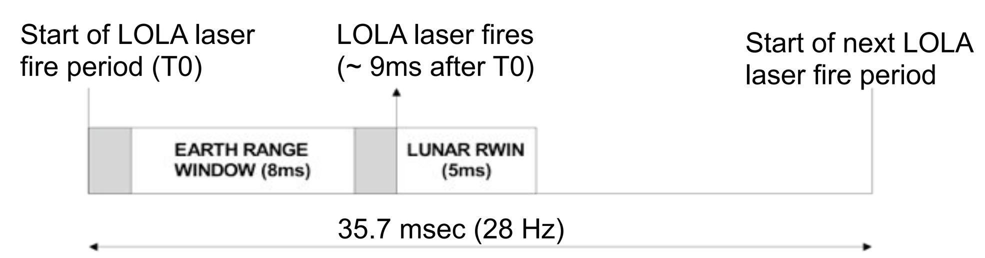


- Ground Segment
  - Transmit 532 nm laser pulses at =< 28Hz
  - Time stamp departure times at ground station
  - Event arrival times recorded by LOLA
  - Compute 1-way range to LRO from the two times



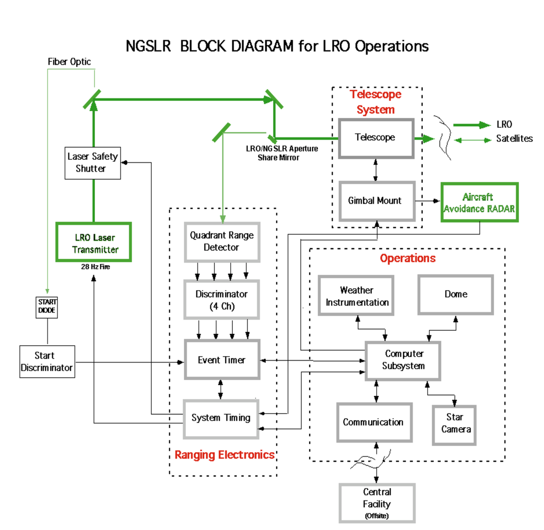
One LOLA Detector does both Earth and Lunar Measurements

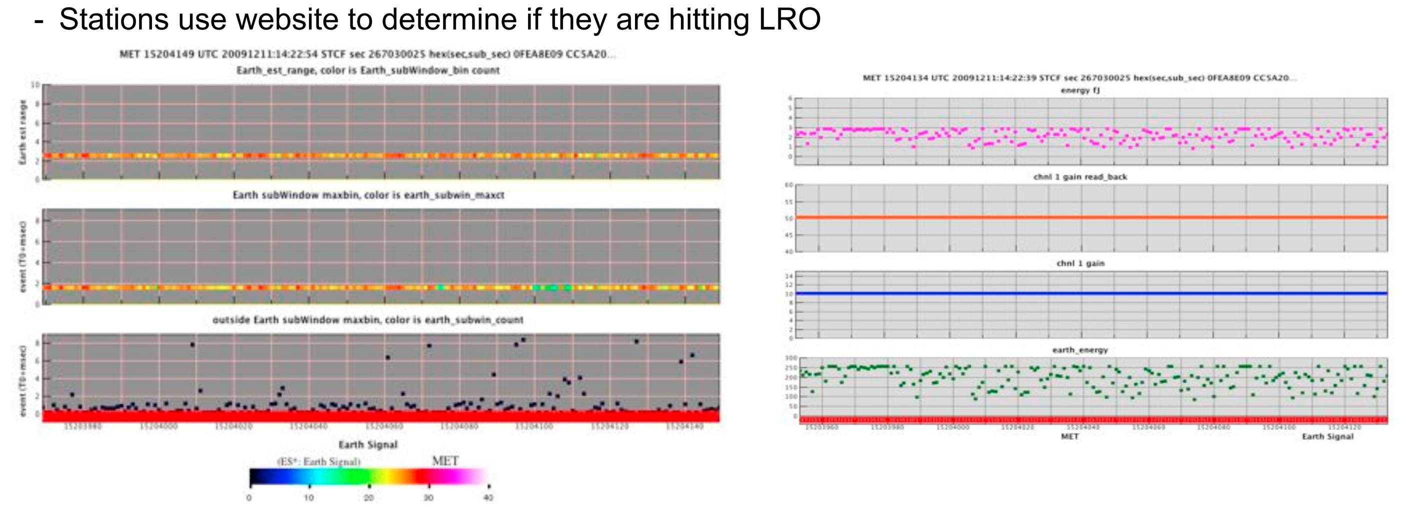
- Two range windows in one detector: 8 msec earth and up to 5 msec lunar.
- Range to LRO changes ~ 5-10 ms over an hour's visibility.
- either
  - synchronize the ground laser fires to LOLA's fire window and LRO's orbit to ensure pulses land in every Earth Window, or
  - fire asynchronously to LOLA (eg 10Hz).



LR operations

- Use predictions (CPFs) generated by GSFC Flight Dynamics Facility (FDF) with accuracy < 4 km (3D, 3 sigma) :
- An SCLK file relates spacecraft time (MET) to UTC for synchronous firing.
- Go/NoGo file. Set to NoGo to stop all stations from firing within 5 mins.
- Fire times recorded at each station:
  - Accuracy to UTC < 100 ns
  - Relative fire time error RMS < 200 ps (over 10 sec).
- Real-time feedback from spacecraft
  - LOLA flight software performs signal processing on LR events
  - Results come down in LOLA housekeeping and are displayed on website
  - Web display latency is between 10 to 30 seconds
  - Stations use website to determine if they are hitting LRO





Participating Stations from the International Laser Ranging Service (ILRS)

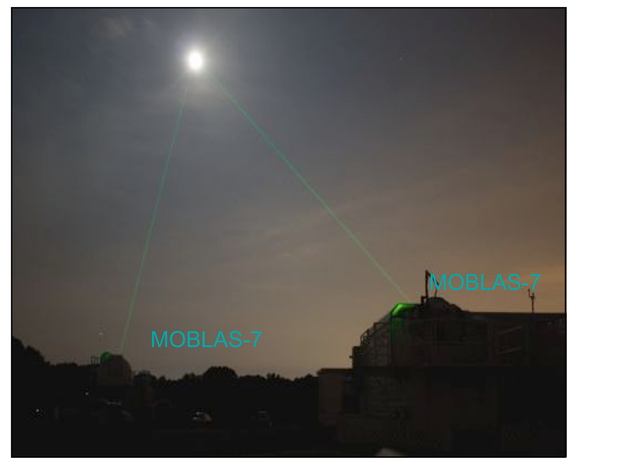
- NASA's Next Generation Laser Ranging System (NGSLR) in Greenbelt, Maryland
- Other ILRS tracking sites ranging to LRO:
  - McDonald Laser Ranging System (MLRS): Texas
  - Herstmonceux: Great Britain
  - Zimmerwald: Switzerland
  - Wettzell: Germany
  - Hartebeesthoek: South Africa
- Ranging to LRO in the very near future:
  - Yarragadee: Australia
  - Monument Peak: California
- Since Jul 4
  - more than 6070 minutes of signal
  - 189 passes

Tracking Station Configuration

- NASA's Next Generation Satellite Laser Ranging System (NGSLR):
  - 50 mJ Northrop Grumman laser (532.2 nm wavelength, 6 ns pulsewidth).
  - Software controlled laser triggers - producing 28 Hz laser fires that arrive at LRO when the LOLA Earth Window is open.
  - 55 microradian laser beam divergence (~20 km spot at moon).
  - Aircraft avoidance radar (FAA regulations for non-eyesafe lasers). Honeywell Event Timer (ET) with 30 picosecond accuracy.
  - Symmetricom Cesium oscillator (CS-4310) provides 10 Mhz time base for ET.
  - TrueTime XL-DC GPS steered Rubidium provides station timekeeping.
  - Arcsecond precision tracking mount, pointing accurate to a few arcseconds.
- Station fire rate and probable events per second in LOLA Earth Window with system configurations:
  - Transmit 532 nm laser pulses at =< 28Hz
  - Time stamp departure times at ground station accurate to <100 ns of UTC
  - Resolution of recorded time of each shot: <100 psec resolution
  - Relative shot-to-shot interval knowledge over a 10 sec period: <200 ps (1 sigma)
  - Event arrival times recorded by LOLA
  - Compute 1-way range to LRO from the two times

Tracking station	Synchronous	FireRate	Events/second in Earth Window	Energy per pulse at LRO (fJ/cm^2)
NGSLR	YES	28Hz	28	2 to 5
McDonald	NO	10Hz	2 to 4	4 to 10
Zimmerwald	YES	14Hz	14	2 to 10
Herstmonceux	YES	14Hz	14	1 to 3
Hartebeesthoek	NO	10 Hz	2 to 4	1 to 2
Yarragadee	NO	10 Hz	2 to 4	1 to 2
Monument Peak	NO	10 Hz	2 to 4	1 to 2
Wettzell	NO	7 Hz	7	1 to 2

Tracking LRO from Greenbelt, MD



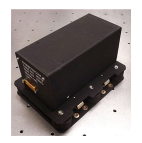
LOLA/LR Clock Oscillator Characteristics

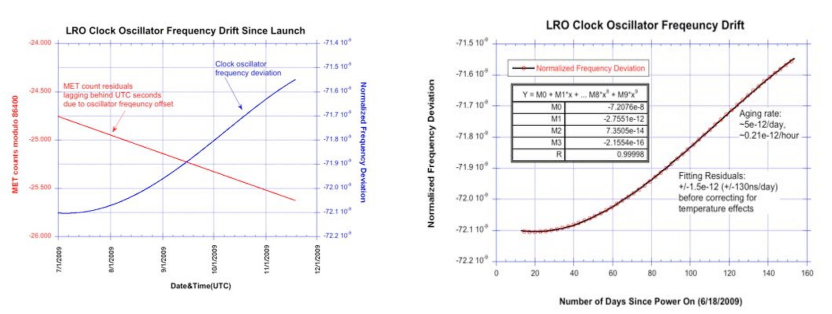
Mid to Long Term Stability per s/c house keeping data

Symmetricom 9500 series Oven Controlled Crystal Oscillator

Size: 180x130x110 cm; Mass: 2.5 kg; Power: 4.5 W.

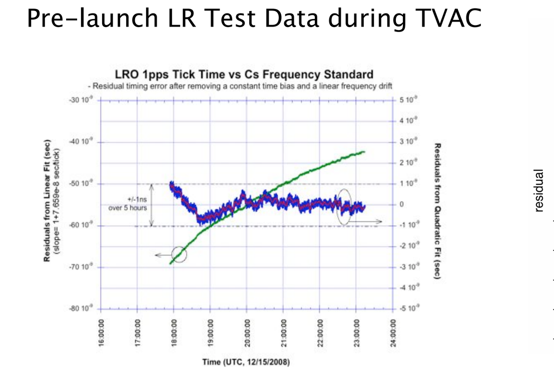
- Clock frequency based on routine spacecraft time keeping operations

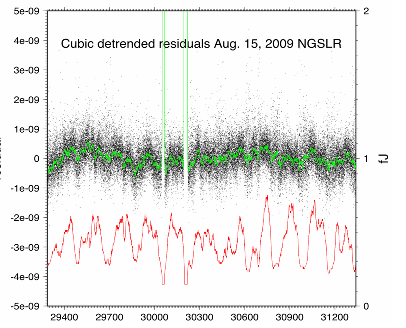




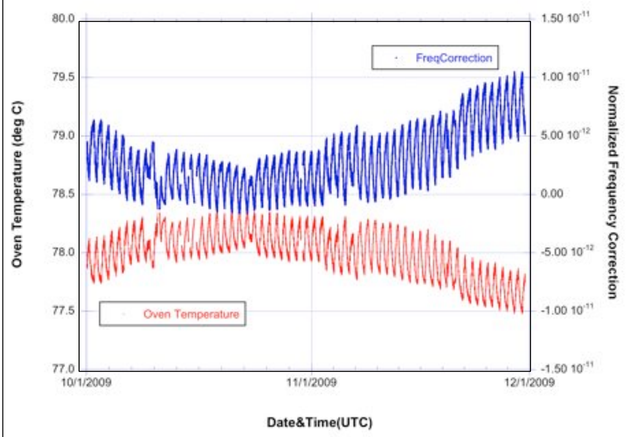
- Oscillator long term frequency stability is about +/-1.5e-12 per day before removing the temperature effect.
- Large thermal mass smoothes out orbital temperature effect
- Daily and long term temperature effects can be removed to <<1e-12 using the model developed during ground testing.

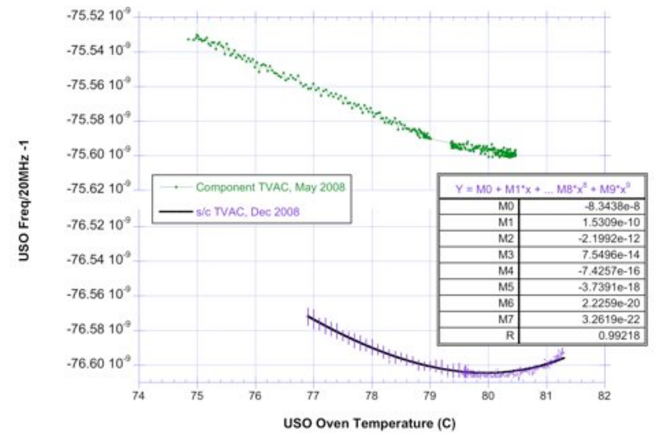
Frequency Stability via LR data





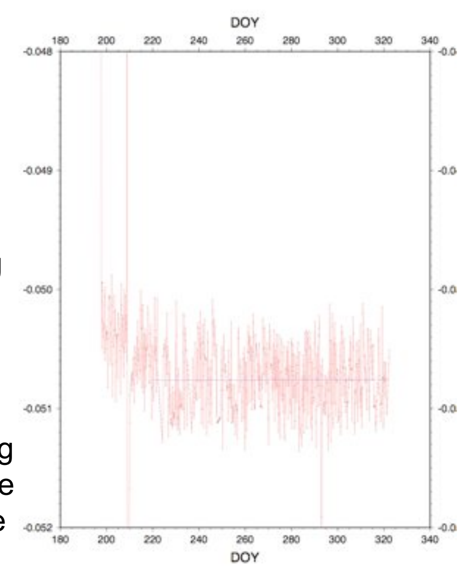
- LRO time base is stable to a few nanoseconds over several hours after removing a linear frequency aging rate based on both ground testing data and in orbit data.
- LR measurements helped to verify the spacecraft time (e.g., LRO MET counter reading 8326775 9/23/09 00:00:00.321424484 (UTC))



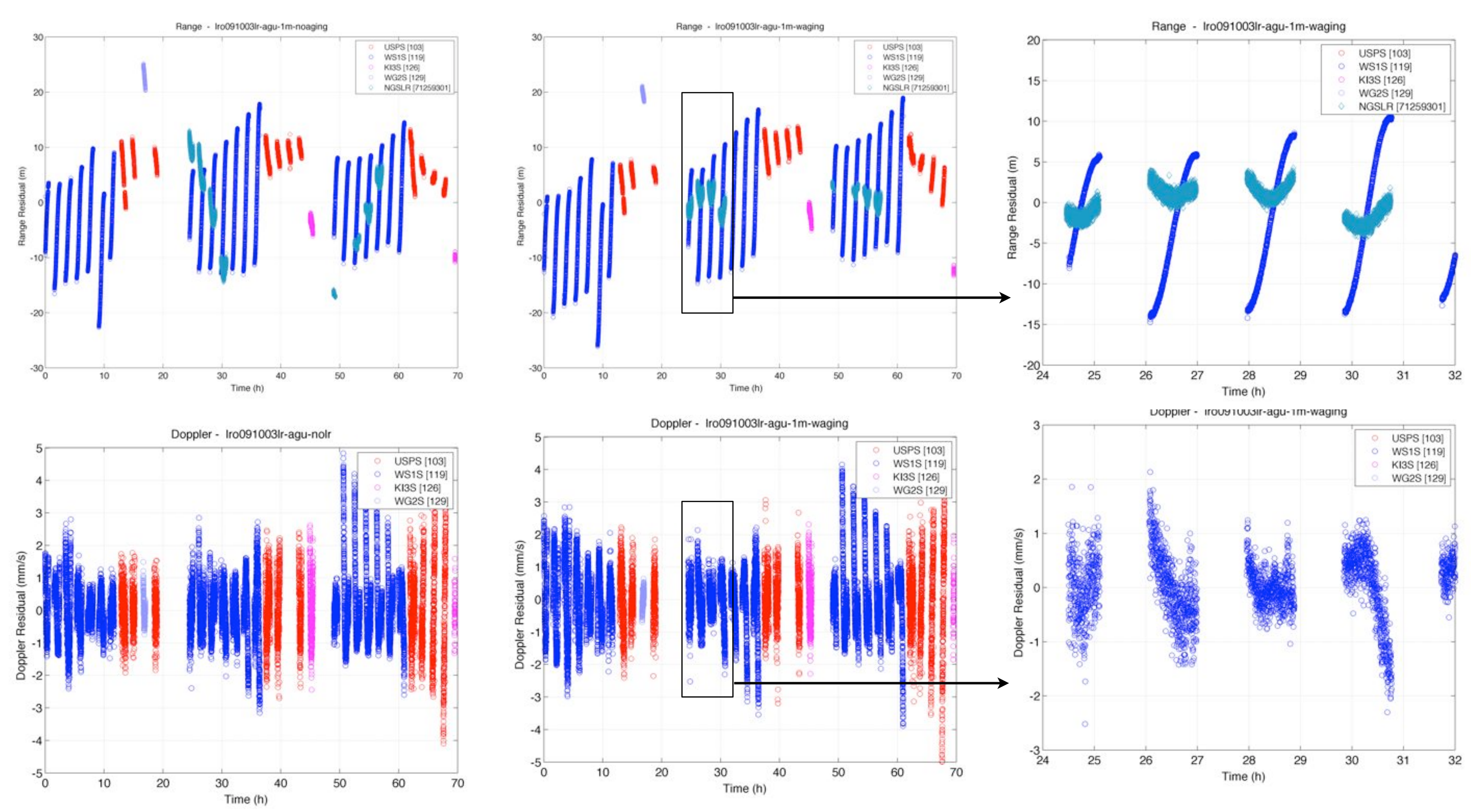


- On orbit oscillator temperature and temperature correction. Nominal operating temperature is about 78º (*left*)
- Oscillator frequency dependence upon temperature (*right*).

- the drift rate of the LRO project-supplied spacecraft clock is approximately 1.00000007178 seconds per 1 pps clock tick.
- The plot shows the trend of the LRO clock about this rate at some arbitrary offset, which is expected to drift very slowly.
- The LRO clock appears to maintaining be ~1 ms knowledge after the first couple months, with intermittent glitches, and an unknown bias which can easily be determined.
- Thus the clock offset for Laser Ranging and LOLA can be predicted much more easily just using this rate, obviating the need for the SCLK and LRO to LOLA time offsets (STCF).



(very) Preliminary LRO orbit determination Results



- no LR data:
  RMS$_{range}$ ~ 7.85m
  RMS$_{doppler}$ ~ 0.91mm/s
  N$_{range}$ = 16638
- with LR data:
  RMS$_{range}$ ~ 6.93m
  RMS$_{doppler}$ ~ 0.98mm/s
  N$_{range}$ = 31416

Orbit Differences

Doppler+Range vs Doppler+LR

	Radial (m)	Cross (m)	Along (m)
Minimum	-2.91	-28.61	-9.21
Maximum	2.96	28.25	13.23
Average	0.05	-0.04	2.58
RMS	1.51	19.54	5.85

Orbit Differences

Doppler+Range+LR vs Doppler+LR

	Radial (m)	Cross (m)	Along (m)
Minimum	-0.41	-9.76	-3.77
Maximum	0.39	9.89	4.03
Average	-0.02	0.02	0.51
RMS	0.21	6.76	2.17